ON THE GEOLOGY OF THE ALKALI ROCKS IN THE TRANSVAAL

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CONTENTS

INTRODUCTION

In June 1910 I studied the geology of the occurrences of nepheline syenites in the Transvaal, and the results were published in the same year in a paper, "Oorsprong en Samenstelling der Transvaalsche Nepheliensyenieten," which contains a contribution to the geology and a petrographical description of the nepheline syenites and various allied rocks. In the following pages some geological questions will be treated more in detail and the main results of recent work of the Geological Survey of South Africa are added.

I am much indebted to Professor G. A. F. Molengraaff, of Delft, who placed his collection of rocks at my disposal, while the text has been much improved by his valuable suggestions; and also to Professor A. Lacroix, of Paris, the rock material being studied for the greater part in his laboratory.

For assistance during my stay in South Africa, my best thanks are due to the staff of the Geological Survey, particularly to Mr. A. L. Hall, who furnished some rock specimens from Rietfontein [451] and Spitskop [463].[1]

As a guide to the stratigraphy and the geological dates mentioned below, a table of the Transvaal formations is entered (see Table I).

IGNEOUS COMPLEX OF THE BUSHVELD

The nepheline syenites of the Transvaal make part of a complex of igneous rocks, which is intrusive as a laccolith or laccolithic sheet between the upper strata of the Transvaal system and the strata of the unconformably overlying Waterberg system.

The laccolithic character of this complex was recognized by Molengraaff,[2] who grouped them under the name "plutonic series of the Bushveld";[3] it includes igneous rocks, which have a high soda content as a common character. The name used by other authors, "igneous complex of the Bushveld" or "Bushveld igneous complex," has the same signification and can be considered as the official one, because the Geological Survey of the Transvaal has adopted it.

PLACE OF THE MAIN TRANSVAAL LACCOLITH

The western boundary of the part of the complex in the Central Transvaal, which has been uncovered by erosion, is found nearly 15 km. to the west of the Marico River; the eastern one, nearly 25 km. to the west of Lydenburg; the medium breadth is nearly 100 km.

But probably it covers a much larger area; at least it appears again between the Magalakwin River and the sources of the

[1] Throughout this paper numbers in brackets refer to official designations for farms in South Africa.

[2] G. A. F. Molengraaff, "Géologie de la République Süd-Africaine du Transvaal," *Bull. de la Soc. Géol. de France*, Série 4, T. I, 1901, p. 13.

[3] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 42.

Matlabas and to the north of the Palala Plateau, where it extends to the north to near the Limpopo, nearly 30 km. to the south of the northern boundary of the Transvaal.[1]

BOTTOM OF THE LACCOLITH

The bottom of the laccolith is formed everywhere by the upper strata of the Pretoria series, generally consisting of Magaliesberg quartzite.

Therefore the rocks of the laccolith in the Central Transvaal are for the greater part surrounded by the upper Pretoria strata; in the strata of the Transvaal system, which dip everywhere toward the central part of the complex, the dip of the strata decreases when the distance from the complex increases. Because the Magaliesberg quartzites of the Pretoria series have specially resisted erosion we now see them as a ridge surrounding the complex.

We see that the bottom of the laccolith is determined, but the the place of the roof of the laccolith is uncertain.

ROOF OF THE LACCOLITH

The part of the laccolith, which has not been uncovered by denudation, is covered by the strata of the Waterberg system and partly by the younger strata of the Karroo system. Between the basal conglomerate of the sandstone series of the Waterberg system and the underlying rocks of the Bushveld complex we sometimes find a series of felsitic rocks, which other authors have considered as being directly connected with the deep-seated rocks of the laccolith, but which the Geological Survey of the Transvaal regards as a lower division of the Waterberg system.

The Waterberg system then includes:

Waterberg system	Upper Division	Sandstones, grits, and conglomerates
	Lower Division (Volcanic series)	Felsites and allied volcanic rocks with interbedded shales

[1] G. A. F. Molengraaff, "Geologische Aufnahme der Süd-Afrikanischen Republik," *Jahresbericht über das Jahr 1898*, Pretoria, 1900; G. G. Holmes, "Some Notes on the Geology of the Northern Transvaal," *Trans. Geol. Soc. South Africa*, VII (1904), 51–56.

The roof of the laccolith would, then, not be formed by the sandstone series of the Waterberg system but by the volcanic

TABLE I

Table of the Geological Formations of the Transvaal[1]

Main Igneous Intrusions	Sedimentary Rocks			Age
	Superficial Deposits			
	Unconformity			
	Karroo system	Upper Karroo	Bushveld amygdaloid	?
			Bushveld or Buiskop sandstone	?
		Middle Karroo	Highveld or Beaufort series with coal measures	Permo-Carboniferous
		Lower Karro	Ecca shale series	
			Dwyka conglomerate or tillite	
Bushveld igneous complex intruded as an unconformational laccolithic sheet between the strata of the Pretoria series and those of the Waterberg system	*Waterberg system*			
	Unconformity			
	Transvaal system	Pretoria series		Probably pre-Devonian
		Dolomite series		
		Black Reef series		
	Unconformity			
	Ventersdorp or Vaal River system			?
Old grey granite.—The exact age of the intrusion or the intrusions of this granite is not yet known. The intrusion, however, took place certainly after the deposition of the rocks of the Swaziland system and before the deposition of the rocks of the Transvaal system	Unconformity			
	Witwatersrand system	Upper division, containing the famous auriferous Main Reef series		?
		Lower division		?
	Unconformity			
	Swaziland system			?

series, in which sometimes red granites can be seen clearly intrusive. But the question of the mutual relation between the rocks of the

[1] Cf. G. A. F. Molengraaff, "The Deposits of Iron Ore in the Transvaal," in *The Iron Resources of the World* (Stockholm, 1910), p. 1060.

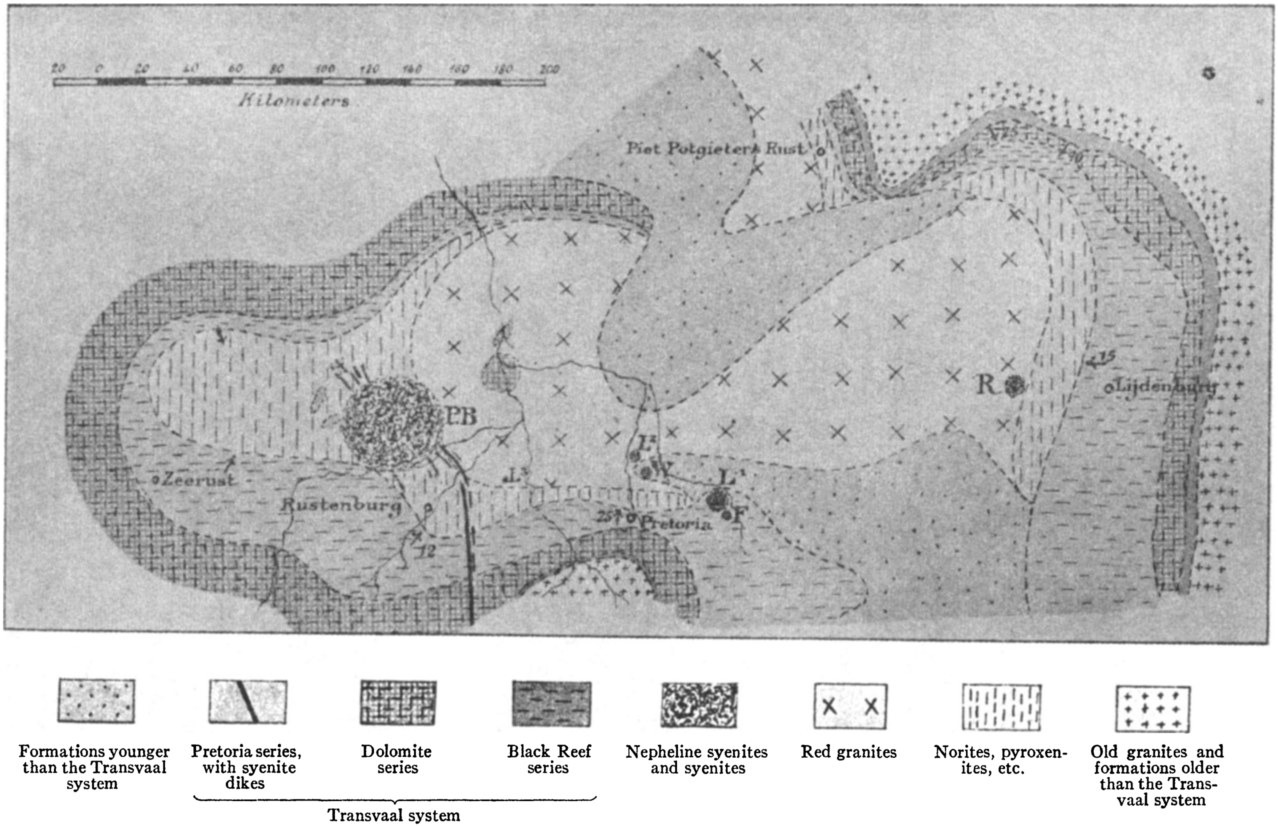

FIG. 1.—Geological sketch map of the Central Transvaal with the occurrences of nepheline syenites and allied rocks*

* Complex of the Pilandsberg: *L*[1], Leeuwfontein [320]; *L*[2], Leeuwkraal [396]; *L*[3], Losperfontein [119]; *F*, Franspoort [426]; *W*, Walmansdal [116]; *R*, Rietfontein [451

Bushveld complex, the volcanic series, and the sandstone series, of which the contradictory facts already were enumerated by Molengraaff,[1] has not been solved in this way.

As far as concerns this mutual relation, the following facts can be considered as certain:

1. The deep-seated rocks are intrusive in the volcanic series.

2. Dikes which are genetically connected with the deep-seated rocks (felsophyres with the red granites, tinguaites with the nepheline syenites) cut through the sandstone series.

3. The volcanic series show the characteristics of effusive rocks and include sediments (shales and sandstones) in the higher horizons.

4. Sometimes more, sometimes less, clearly the sandstone series rest unconformably upon the volcanic series, the transition being characterized by the existence of conglomerates.

5. In the basal conglomerate of the sandstone series felsitic pebbles sometimes occur.

6. Fragments of a conglomerate, which very closely resembles the basal one, are found in the phonolites of the Pienaars River valley.

When we try to make these facts agree with each other, we meet with great difficulties. It seems to be certain that an effusive period has preceded the main intrusion and that both are connected genetically.

But when we admit, for instance, that the sandstone series are older than the effusive and intrusive series, then the occurrence of felsitic pebbles in the basal conglomerate and the more or less distinct unconformity with regard to the felsites, and also the effusive character of the latter ones and their alternation with sediments, are inexplicable. When we admit that the sandstone series are younger than the effusive and intrusive period, then the intersecting dikes, which are the equivalents of the deep-seated rocks, and also the intrusions of red granite in the sandstone series are unexplained.

We could explain the facts in a rather satisfactory way if we admitted effusion and several intrusions from a deeper-seated

[1] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 59.

mother-magma and considered the Waterberg sandstone as younger than the effusive, but older than the main intrusive, period; then, however, there is no genetic connection between effusion and intrusion.

With H. Kynaston and E. T. Mellor,[1] we can admit a prolonged activity of the Bushveld magma, while the sandstone series were deposited between the main intrusive and effusive period and the later intrusions.

That the nepheline syenites are younger than both the norites and the granites will be proved in the following pages. Only detailed geological and petrographical investigations can clear the true succession from the remnants left after the advanced denudation.

In any case, the following reasons make it undesirable to unite the volcanic series and the sandstone in the Waterberg system.

Over large surfaces at the base of the sandstone series we find developed a basal conglomerate, which rests unconformably, not only upon the felsites, but also upon the red granites; and in the Zoutpansbergen we also find them resting upon much older formations, such as the old granites. Thus it forms a geological horizon over the whole of Central Transvaal and marks an extensive unconformity.

As a rule the pebbles of felsites are rare in this conglomerate, although the relative quantity may increase locally and the unconformity be locally less well developed. In the Waterberg district[2] the conglomerate is principally composed of pebbles of jasper, quartzite with magnetite, white quartzite, schistose quartzite with muscovite, quartz, chert, and felsophyre, which, except the felsophyre, belong to the Swaziland system (Barberton series). Consequently this unconformity must be maintained as a horizon of separation, and the volcanic series must be separated from the sandstone series of the Waterberg system and can either be included in the igneous complex of the Bushveld or else considered as a

[1] H. Kynaston and E. T. Mellor, *The Geology of the Waterberg Tin Fields. Memoir No. 4, Geological Survey of the Transvaal*, Pretoria, 1909.

[2] G. A. F. Molengraaff, "Geologische Aufnahme der Süd-Afrikanischen Republik," *Jahresbericht über das Jahr 1898*, Pretoria, 1900.

separate volcanic series, which is younger than the Transvaal system and older than the Waterberg system and the main laccolithic intrusion.

ACCOMPANYING DIKES AND INTRUSIVE SHEETS

Except the basic rocks, which alternate with the shales and quartzites of the Pretoria series and which are perhaps genetically connected with the intrusion, numerous syenite dikes cut through the Pretoria series and the Dolomite series, and intrusive sheets of red and grey syenite are found in the dolomites. The well-known dike of porphyritic nepheline syenite of the station Wonderfontein in the Potchefstroom district can be followed over Breedts Nek in the Magaliesbergen as far as the nepheline syenites of the Pilandsberg.

At the contact of the intrusive sheets, which have a thickness of three to forty meters, the syenite is finer-grained to microcrystalline, and the dark dolomite has been changed into white marble.

TECTONIC CHANGES CONNECTED WITH THE INTRUSION

The study of the Transvaal system in the neighborhood of the laccolith proves that there are numerous dislocations directly connected with the intrusion.[1]

The strata sank under the weight of the intrusive mass; this explains the increasing of the dip, when the distance from the complex decreases, and also explains why the complex is surrounded by a ridge of harder sediments, which dip toward the central part. In the neighborhood of Pretoria and from there to the west, as far as Rustenburg, we see the ridge of the Magaliesberg quartzites uninterrupted, the strata dipping toward the intrusive complex.

To the east of Pretoria is a series of step faults, which can be followed easily in parallel ridges, which consist of quartzites of the Pretoria series.

We see the dislocations in a remarkable manner where the periphery of the complex forms a re-entering angle as, for instance, at Franspoort east of Pretoria. The ridge of the Magaliesberg

[1] This question was discussed in detail by Molengraaff; cf. *Geology of the Transvaal* (Johannesburg, 1904), p. 50.

quartzites and the accompanying Daspoort and Timeball quartzites here suddenly bend to the southeast. The dip of the strata continues toward the red granites, but the outer ridge of the Magaliesberg quartzites has been fractured and extended in length; the ridge is broken by "poorten." The inner ridges (Daspoort and Timeball Hill quartzites) were strongly pressed in a direction slightly oblique to the strike of the strata. All this is clearly shown by the grouping of the quartzite hills in the neighborhood of Pretoria. That the intrusion and dislocations are directly connected is also evident from the study of the zones of contact in the surrounding sediments in disturbed and undisturbed regions.

CONTACT METAMORPHISM

The quartzites, clay-slates, and "greywackes" of the Transvaal system are strongly metamorphosed by the intrusion of the laccolith. The contact phenomena in connection with the laccolith were first mentioned by Molengraaff and later studied in detail by Hall.[1] The quartzites of the Magaliesberg Range are recrystallized and consist of more or less hexagonal quartz crystals, which sometimes attain a diameter of more than one centimeter; in the clay slates cordierite, andalusite, and biotite appear. The metamorphism decreases when the distance to the laccolith increases, but even the rocks of the dolomite series are metamorphosed. Where the Transvaal system is much disturbed and has undoubtedly been exposed to high pressure, the metamorphosed rocks show a different character in their structure, as well as in their mineralogical composition. These rocks are connected by transitions with the pure contact-rocks of the undisturbed regions.

Muscovite, glaucophane, and zoisite, which are characteristic for the dynamometamorphic crystalline schists, and in small quantities the contact minerals, cordierite, andalusite, and tourmaline, occur in the metamorphosed rocks. Hall decides upon the contemporaneous action of contact and dynamometamorphism in the disturbed regions, from which it is once more evident that the intrusion was directly connected with the dislocations.

[1] A. L. Hall, "Über die Kontaktmetamorphose an dem Transvaalsystem im östlichen und zentralen Transvaal," *Tschermaks Min. u. Petr. Mitt.*, Bd. XXVIII, Heft 1–2 (1909), pp. 115–52.

ROCK TYPES OF THE BUSHVELD COMPLEX

1. *Red granites.*—The acid rocks of the laccolith are amphibole-biotite granites, which are very poor in dark constituents. Principally they show typical granophyric structure. They differ petrographically from the old granites, in essential features enumerated by Molengraaff.[1] In the red granites muscovite is entirely wanting.

2. *Norites, gabbros, and pyroxenites (with segregations of iron ore).*—Nearly everywhere at the periphery of the red granites we find a zone of basic and ultra-basic rocks. The basic rocks are found near the western and southern part of the Pilandsberg; they accompany the Magaliesberg quartzites in a south-southeasterly direction to the environs of Rustenburg, where they bend to the east in the direction of Pretoria. The Zwartkoppies and Pyramids have been given their respective names from the color and the form of the small hills, which are composed of these rocks. Finally, they are found from the environs of Belfast to those of Piet Potgietersrust; still farther to the north they are in contact with the old granites. Iron ore has been segregated from these basic rocks at several places; lenticular masses of magnetite are developed nearly everywhere around the Bushveld. At some places these masses are thicker than one hundred meters. The iron ore is magnetite, sometimes with chromite. In the norites the percentage of magnetite goes on increasing, as one approaches the pure magnetite. Ultra-basic pyroxenites and peridotites fill the shallow basin to the West of the Pilandsberg, bounded on the south by the Schurveberg and the Zeerust Hills, on the west by the Marico Hills, and on the north by the Dwarsberg.

3. *Nepheline syenites and syenites.*—These rocks, of which the mode of occurrence and the composition are more fully described in the following pages, are uncovered at several places, often near the boundary of norites and granites.

PNEUMATOLYSIS

As a result of the cooling down and contraction of the intrusive complex and the pressure upon the surrounding strata, numerous

[1] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 44.

fissures were formed, in which different minerals crystallized from the circulating emanations of the magma. The numerous occurrences of tin ore are genetically connected with the red granites of the Bushveld. The copper and silver ores of the Albert mine and the cobalt ores of Balmoral are found in red granite. Finally, we find numerous ore deposits in the Pretoria series, the origin of which is probably directly connected with the intrusion of the Bushveld complex.[1]

THE OCCURRENCES OF ALKALI ROCKS

Common to the occurrences of alkali rocks is the abundance of nepheline syenites. They are exposed at the following places:

1. In the Pilandsberg (Rustenburg district), where they are accompanied by syenites, effusive rocks, and dike rocks.
2. At the boundary of the farms Leeuwfontein [320] and Zeekoegat [287], northeast of Pretoria, where they are accompanied by syenites, leeuwfonteinites, effusive rocks, and dike rocks.
3. On the farms Rietfontein [451] and Spitskop [463], west of Lijdenburg.
4. On the farm Franspoort [426], south of Leeuwfontein [320] (Pretoria district).
5. On the farm Walmansdal [116], northwest of Leeuwfontein [320].
6. On the farm Leeuwkraal [396], still farther to the northwest.
7. On the farm Losperfontein [119] (Rustenburg district).
8. Numerous dikes can be followed from the Pilandsberg in a northwesterly and a southerly to southeasterly direction.

[1] G. A. F. Molengraaff, *Geology of the Transvaal* (1904), p. 52; A. L. Hall, "Geological Notes on the Bushveld Tin Fields, etc.," *Trans. Geol. Soc. South Africa*, VII (1905), 47–55; F. H. Hatch and G. S. Corstorphine, *Geology of South Africa* (London, 1909), p. 216; E. T. Mellor, "Field Relations of the Transvaal Cobalt Lodes," *Trans. Geol. Soc. South Africa*, X (1907), 36; H. Kynaston, "Anniversary Address of the President of the Geological Society of South Africa for 1908," *Trans. Geol. Soc. South Africa*, XII (1909); H. Recknagel, "On Some Mineral Deposits in the Rooiberg District," *Trans. Geol. Soc. South Africa*, XI (1908), 83; "On the Origin of the South-African Tin Deposits," *Trans. Geol. Soc. South Africa*, XII (1909), 168; H. Merensky, "The Rocks Belonging to the Area of the Bushveld Granite Complex in Which Tin May Be Expected, etc.," *Trans. Geol. Soc. South Africa*, XI (1908), 25; H. Kynaston and E. T. Mellor, "The Geology of the Waterberg Tin Fields," *Memoir No. 4, Geological Survey of the Transvaal*, Pretoria, 1909.

THE PILANDSBERG

Where the ridge of the Magaliesberg quartzites—the direction of which was southeast and northwest, to the north of Rustenburg—bends again to the west, a mountain group arises from the rolling

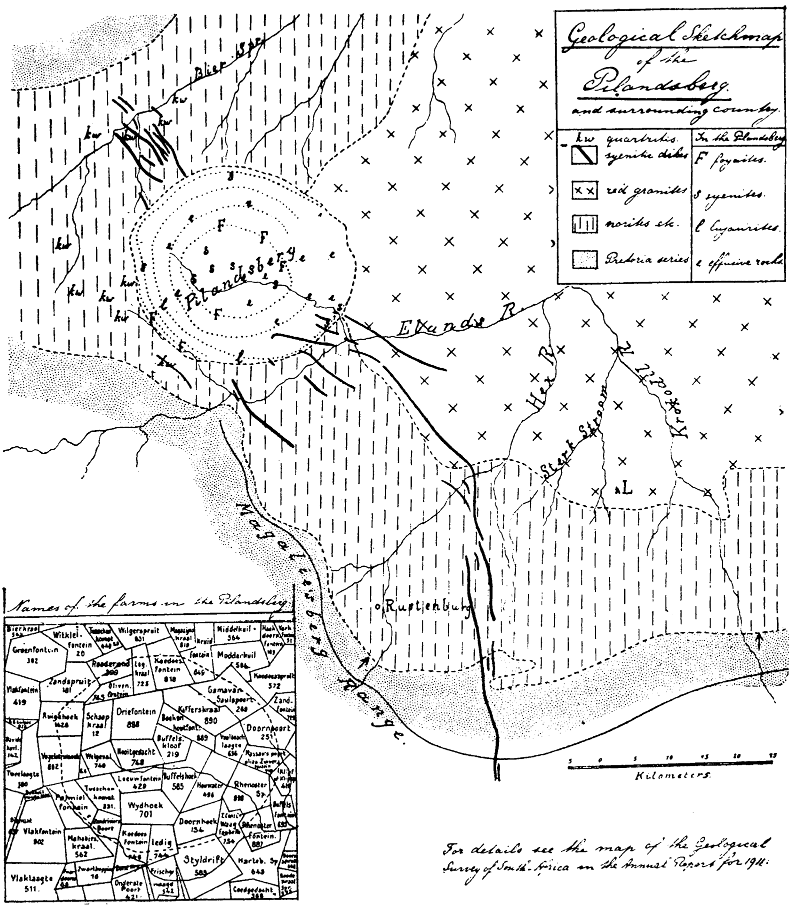

FIG. 2.—Geological sketch map of the Pilandsberg

and undulating country of norites and granites. It has an almost circular outline with a diameter of 15 miles from north to south and 18 miles from east to west. Long ridges and isolated mountains are separated by broad valleys, in which small rivers, dried up in winter, have cut deep valleys with vertical walls.

The first explorer who mentioned the composition of the Pilandsberg and the surrounding region was Adolf Hübner, in his description of a voyage from Potchefstroom to Inyati.[1] Evidently he had observed the peculiar character of these rocks, because he writes: "Am meisten Beachtung verdient wohl das unten zu beschreibende Gestein der Pilandsberge, welches entschieden als ein basisches plutonisches Gestein zu den Grünsteinen gerechnet werden muss." He crossed the Magaliesberg Range along the Hex River at Olifants Nek and traveled from there to Morgenzon [427] (the same direction which the road from Rustenburg to the Pilandsberg still follows); as the rock of the plain of Rustenburg he mentions a typical medium-grained greenstone, which near the contact with the rocks of the Magaliesberg Range crops out in thick sheets.[2] Then he crossed the Elands River and reached the Pilandsberg, which, he says, consists of mountains of greenstones from about 400 to 600 feet high. The meaning of his sentence, "Die Gesammtheit der Quarze bildet ein wahres Massengebirge," is not very clear. He mentions that a part of the mountains consists of a rock which seems to be a "hornblende porphyry," but which shows a syenitic character on closer examination. Because it consists of two minerals, a red "felsite" and a black amphibole, Hübner says that it is not a normal porphyry, though the red feldspar (orthoclase) predominates. The amphibole does not form crystals, but shows rather regular forms. As an interesting feature of this perhaps quite new rock, he mentions the numerous inclusions of clay slate and granite, which do not show any contact metamorphism. According to Hübner, this rock would cover a large area in the Pilandsberg. At several places, e.g., behind the negro town on Saulspoort [369] in the northeastern part of the mountains, granites and eruptive breccias, which contain fragments of porphyrite and granite, occur. Because Hübner mentions that he visited the missionary station on Saulspoort, he perhaps speaks about these rocks, which occur in the neighborhood of syenites with red feldspars.

[1] Adolf Hübner, "Geognostische Reisen in Süd-Africa," *Peterm. Geogr. Mitt.*, XVIII (1872), 424, 426.

[2] These rocks probably are the norites with schistose structure in the margin of the igneous complex of the Bushveld.

Nearly at the same time as Hübner, Carl Mauch[1] made geognostical studies in the central part of South Africa. In a chapter, "Mein erstes Jahr in der Transvaal Republik," he describes his "Irrfahrten in den Pilaans-Bergen." Coming from Rustenburg, he passed a conical hill and entered the central part of the mountain complex and found "quartz porphyries" with a violet-brown groundmass in the bed of a rivulet. After nearly perishing with hunger and thirst, he was received hospitably in the house of the missionary, who still lives in the native *stadt* on Saulspoort. From the western part of the mountains he mentions pieces of copper ore, magnetite, fluorine, and pebbles of gneiss. Most probably his quartz porphyries are the rocks without quartz, with porphyritic feldspars in a reddish, dense or fine-grained groundmass, which are the effusive equivalents of the syenites and nepheline syenites of this region. His gneiss probably is the schistose lujaurite which covers large areas in the western and southern part of the mountains.

In his sketch of the South-African Republic, G. A. F. Molengraaff[2] gives a review of the knowledge about the rocks of the Bushveld, and here the results of Mauch and Hübner are mentioned.

In 1898 J. A. L. Henderson[3] described a syenitic rock from the Pilandsberg as pilandite. The true character of the rocks of the Pilandsberg was recognized by Molengraaff[4] in 1904. In a short geological description of the Pilandsberg and a part of the Rustenburg district he mentions that different varieties of foyaites are of widespread occurrence and the schistose varieties, which are very rich in aegerine, are compared with the lujaurites of Greenland. The rock specimens, which Molengraaff collected, were studied by me, and the results of this study were published in the petro-

[1] Carl Mauch's "Reisen im Innern von Süd-Afrika, 1865–1872," Ergänzungs-Bd. VIII (1873–74), *Peterm. Geogr. Mitt. No. 37.*

[2] G. A. F. Molengraaff, "Schets van de Bodemgesteldheid van de Zuid-Afrikaansche Republiek," *Tijdschr. Kon. Aardr. Gen.* (Leiden, 1890), p. 604.

[3] J. A. L. Henderson, *On Certain Transvaal Norites, Gabbros, Pyroxenites and Other South-African Rocks.* London, 1898. Dulau and Co.

[4] G. A. F. Molengraaff, "Preliminary Note on the Geology of the Pilandsberg and a Portion of the Rustenburg District," *Trans. Geol. Soc. South Africa*, VIII (1905), 108.

graphical part of my first paper. In the winter of 1910 I visited the occurrences of nepheline syenite in the Transvaal, especially that of the Pilandsberg (during the last two weeks of June).

After this visit I was able to give a brief description of the general geology of the neighborhood.[1] I showed that these mountains consist of red syenites, nepheline syenites, and their porphyritic and dense equivalents, and, with a sketch map, that the main rock types are disposed in concentric circles. As far as concerns the red syenites, I was able to show that they often are covered by the effusive rocks, while they probably were older than the nepheline syenites of the complex. There was clear evidence that the rocks of the Pilandsberg intrusion are younger than the granites and norites of the igneous complex of the Bushveld; dikes, which are genetically connected with the intrusion, cut through the granites and norites. The intrusion of nepheline syenites on Leeuwfontein [320] was shown to be certainly younger than the Waterberg system, because a dike of tinguaite, which has the same chemical composition as the normal foyaites of Leeuwfontein, cuts through Waterberg sandstones and conglomerates on Paardefontein [338].

The mapping of the Pilandsberg and surrounding area was carried out in the next year by Dr. Humphrey, in company with Dr. P. Wagner, in connection with the work of the Geological Survey of South Africa.[2] Humphrey divides the whole of the rocks into two main groups: the nepheline syenites and phonolites; and the alkali syenites and trachytes. Each of these groups contains a plutonic and an effusive representative and "the reason for this classification is that the rocks forming the Pilandsberg are the denuded remnants of what was once a stupendous volcano, comparable in size with the greatest of the present-day active volcanoes."

General character of rocks.—The foyaites and other allied rocks in Professor Molengraaff's collection have been described by me

[1] H. A. Brouwer, *Oorsprong en samenstelling der Transvaalsche Nepheliensyenieten* (1910), pp. 12–29.

[2] W. A. Humphrey, "The Volcanic Rocks of the Pilandsberg," *Trans. Geol. Soc. of South Africa*, August 19, 1912; "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 77.

in detail. Because the study of the alkali syenites and effusive rocks which were collected during my visit in 1910 has been postponed by my departure for the East Indies, we will mention the most characteristic features of the latter rocks, as they have been briefly described by Humphrey.

The richness in pneumatolytic and thermal minerals (especially fluorspar) is characteristic for the rocks of the whole region; accordingly the loss on ignition is always considerable.

Besides the coarse- to medium-grained intrusive rocks and the effusive ones, transitional types have a great development. A series of porphyrites which graduate through all the types between true lavas, intrusive sheets, and dikes often form an unbroken series paralleling the effusive rocks.

Nepheline syenites: The nepheline syenites partly belong to the group of the foyaites and are usually coarse-grained. They are connected by transitions with the lujaurites, which are characterized by the abundance of small needle-shaped crystals of aegirine and are quite similar to the lujaurites of Greenland and the peninsula of Kola. The latter rocks principally are found in the southern part of the mountains, while lujauritic rocks only exceptionally occur in the central part. The foyaites have been frequently found by Humphrey in dikes, traversing the various effusive rocks and the red syenites.

If we divide the foyaites according to the character of the dark minerals, we find that nearly all the subgroups are represented and, in the porphyritic varieties, we also find aegirine, alkaline amphiboles, and biotite, either characterizing different rock types or occurring together in the same rock. The amphiboles are rich in alkalies and often show peculiar properties which are similar to those often mentioned in the literature of the foyaitic and theralitic rocks. Their optical and chemical properties have not yet been studied in detail, but they are known to have the properties of the barkevikitic, kataforitic, or arfvedsonitic amphiboles.

The isolated range of hills to the southeast of the Pilandsberg proper, which bends around with the lujaurites, consists of aegirine-amphibole foyaites, in which the amphibole has a pronounced zonal structure. The differences in color are progressive from brown

in the central part to green in the margin, while a turning of the plane of optic axes from parallel to the plane of symmetry in the central part to normal to it in the margin was often observed. The extinction angles in sections parallel to [010] are up to 40°. Amphiboles in which the plane of optic axes is normal to the plane of symmetry have also been found in pegmatitic segregations in aegirine-amphibole foyaites on Buffelspan [585]. Their angle of optic axes is very small and the extinction angle **b**:*c* is about 14°. In rocks from Wijdhoek [701] many properties of the amphiboles agree with those of the green amphiboles which Ussing[1] described in rocks from Greenland.

Coarse-grained foyaites are largely developed in the central, and also in the northern, part of the mountains. The hills and a part of the valley on and near Boekenhoutfontein [889] consist of foyaites, which contain aegirine and sometimes are very rich in biotite; more to the south, at Buffelspan [585], coarse-grained aegirine-amphibole foyaites are found. Rocks with the same structure occur in the western part of Houwater [496] and gray foyaites cover a large surface on Schaapkraal [12]. Leucocratic foyaites with aegirine as the only dark constituent are found in the western part of Wijdhoek [701], near the eastern boundary of Tusschenkomst [331]; they are associated with aegirine-amphibole foyaites. They form a complex of isolated small hills in a valley, surrounded by ridges of effusive rocks. The foyaites can be followed to the southern part of Leeuwfontein [429] and to Welgeval [749]. At Wijdhoek [701] they show a considerable amount of variation in structure and composition; we find gray feldspar rocks, which contain biotite as the only dark constituent, varieties which are rich in nepheline, and porphyritic equivalents in which the dark minerals appear as phenocrysts enclosing the elements of the fine-grained groundmass.

The lujaurites are characterized by their richness in fine needles of aegirine. In a forthcoming petrographical paper this group will be described in detail. Aegirine always predominates; arfved-

[1] N. V. Ussing, "Mineralogisk-petrografiske Undersögelser of Grönlandske Nefelinsyeniter og beslaegtede Bjaergarter," *Meddelelser om Grönland*, XIV (1894), 210.

sonite is a rare constituent of the rocks from the Pilandsberg, while true arfvedsonite lujaurites have been described by Ussing from Greenland. The lujaurites are connected with the foyaites by rock types poorer in dark minerals, aegirine with the needle form gradually disappearing. Like the lujaurites from other regions (Greenland, Kola peninsula, and Los islands), the rocks of the Transvaal are characterized by an abundance of rare minerals. For example, the new mineral molengraaffite,[1] of the eucolite group, which sometimes occurs in the foyaites, is very common in these lujaurites.

At both sides of the Rustenburg road, on Ledig [744], we find tinguaitic rocks and porphyritic lujaurites between the high lujaurite hills and the norites; to the east the lujaurites can be followed to Doornhoek [134]. Their southern parts are covered by effusive rocks. To the northwest, bending round with the periphery of the Pilandsberg, we can follow the lujaurites to the southwestern part of Wijdhoek [701]; farther to the northwest the periphery of the complex is formed by red to light-red syenitic rocks. On Tusschenkomst [331] we find the same lujaurites in contact with the effusive rocks, where a valley separates ridges of the two rocks.

The tops of the eroded lujaurite ridges are similar to those of inclined crystalline schists.

We find the lujaurites and their porphyritic equivalents also in the western, northern, and northeastern part of the complex, beside the red syenites; in the eastern part, where the effusive rocks have their greatest development, the latter rocks cover the whole surface from the periphery to the central foyaites. Probably the lujaurites occur there at greater depth. The nepheline syenites and the allied rocks which hitherto have been studied microscopically belong to the following groups:

1. Aegirine foyaites
   Leucocratic rocks
   Mesocratic rocks
   Foyaitic lujaurites

[1] H. A. Brouwer, "Molengraaffit, ein neues Mineral in Lujauriten aus Transvaal," *Centralbl. f. Min., etc.*, 1911, p. 129.

2. Lujaurites
   a) Eucolite-molengraaffite lujaurites
   b) Eucolite lujaurites
   c) Eucolite-astrophyllite lujaurites
   d) Aenigmatite lujaurites
   e) Lujaurites without eucolite
3. Aegirine-amphibole foyaites
4. Aegirine-biotite foyaites
5. Lujaurite porphyries
6. Aegirine-nepheline syenite porphyries without foyaitic structure
7. Aegirine-amphibole-biotite-nepheline syenite porphyries
8. Tinguaite porphyries

Syenites: The syenites generally have a red or reddish color; they principally consist of feldspar, while the dark-colored minerals have usually been altered into chlorite. Iron ores, titanite, apatite, and fluorspar are further constituents of these rocks.

Humphrey[1] mentions that the red syenites of the eastern, western, and central parts of the Pilandsberg have various points of dissimilarity in the hand specimens; those of the east, on Rhenosterspruit, being almost entirely composed of feldspar, while the other localities furnish rocks in which is much iron ore. The latter rocks are very decomposed. The feldspars are microcline, orthoclase, and anorthoclase. Two analyses of red syenites, which have been published in the *Annual Report of the Geological Survey of South Africa* for 1911, show that there are considerable differences in chemical composition between the rocks of this group. A red syenite from Nooitgedacht [748] contains 8 per cent Na_2O and 2 per cent K_2O, while a red syenite from Rhenosterspruit [609] contains 5 per cent Na_2O and 10 per cent K_2O. The high potash content of some of the syenites tends to connect them with the leucite-bearing effusive rocks, which will be mentioned below.

These red syenites bound the Pilandsberg complex on the northwestern, northern, and southeastern sides. For the greater part they are developed as a massive wall, forming the outermost circle of hills at the periphery of the mountains. The red color of the syenites has given the name to the farm Rooderand [399] and from

[1] W. A. Humphrey, "The Volcanic Rocks, etc.," *Trans. Geol. Soc. South Africa*, 1912, p. 104.

there to Saulspoort [369] the syenites form the periphery of the complex; to the south, along Ruigehoek [326], Vogelstruisnek [602], and Palmietfontein [567], they form a nearly interrupted series of bare, low hills. In the southern part, near the road from Rustenburg to Saulspoort [269], steep lujaurite hills rise from the flat norite country. In the southeastern part, where the Rhenosterspruit leaves the hills, we again see the bare, red syenite hills on both sides of the stream. Along the eastern boundary they are covered by effusive rocks. The syenites are found also in the central parts of the complex; in the southern part of Driefontein [888] numerous hills consist of these rocks. They form a conspicuous feature and from a distance can easily be distinguished from the rounded, bare, felsite ridges. We find them also in the southeastern part of Welgeval [749], on Nooitgedacht [748], Buffelskloof [219], Leeuwfontein [429], Buffelspan [585], and Houwater [496]. Near the houses on Nooitgedacht [748], in the valley of a small rivulet, light syenitic rocks with white feldspars occur, which are similar to some varieties of the rocks on Leeuwfontein [320] in the Pretoria district.

By transitions these rocks are connected with the nepheline syenites, as well as with the effusive rocks.

Diorites: As intimately associated with the foyaites and lujaurites, Humphrey[1] mentions the occurrence of diorites, which have their greatest development in the northern part of Boekenhoutfontein [889]. They are also exposed on the summit of the mountain to the southwest of the native *stadt* on Saulspoort and are found as a dike cutting through the norites on Tusschenkomst [446] to the north-northwest of the Pilandsberg complex. The rock is fine grained, has a gray color, and consists principally of augite and labradorite.

Effusive rocks: In my previous paper[2] it has been stated that porphyritic and dense equivalents of the syenites and nepheline syenites have a great development in the Pilandsberg complex. Flow structure is often beautifully developed in these rocks.

[1] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 84.

[2] *Oorsprong en samenstelling der Transvaalsche Nepheliensyenieten*, p. 16.

The effusive rocks have recently been described in some detail by Humphrey in a paper on the volcanic rocks of the Pilandsberg.[1] He divides the rocks into two main groups—the trachytes and the phonolites. The first group contains the effusive representatives of the alkali syenites; the second group, those of the nepheline syenites. An andesitic rock was found on the ridge separating the farm Kafferskraal [890] from Saulspoort [269]. It consists of diallage, diopside, plagioclase, and iron ore in a fine-grained groundmass, and may be an effusive representative of the diorites. The rock has been classed as leucitophyre. The phenocrysts of orthoclase are accompanied by phenocrysts of leucite.

The trachytes attain their greatest development in the eastern portion of the Pilandsberg, on the farms Doornpoort [251] and Vaalboschlaagte [636], where they measure some 5,000 feet in thickness. In this succession the trachytes alternate with red "felsitic"[2] rocks and tuffs, while a thick band of leucitophyres occurs toward the base of the series. These blue-colored leucite-bearing rocks contain phenocrysts of orthoclase and leucite in a groundmass of very finely divided aegirine and feldspar. The phonolites occur in most other parts of the Pilandsberg; they are of a prevailing greenish and bluish color, contrary to the prevailing red of the trachytic series. Typical phonolites on the farm Driefontein [888] contain occasional phenocrysts of feldspar in a finely divided groundmass which consists of feldspar, nepheline, and much aegirine. In the neighborhood of Saulspoort is a rock containing phenocrysts of sodalite in a cryptocrystalline groundmass.

Volcanic breccias and tuffs are widely distributed throughout the Pilandsberg.

The effusive rocks of the isolated mountain at the boundary of Buffelspan [585], Leeuwfontein [429], and Wijdhoek [701] often have a banded appearance, and a beautiful flow structure with parallel arrangement of the feldspar phenocrysts is developed. Well-developed cubes of blue fluorine occur in some of these rocks, while Humphrey mentions the occurrence of leucite crystals. He

[1] "The Volcanic Rocks, etc.," *Trans. Geol. Soc. South Africa*, 1912, p. 105.

[2] Felsite is a field term under which Transvaal geologists comprise a great diversity of rocks: quartz porphyries, felsites, phonolites, tinguaites, andesites, etc.

found the effusives to form a thick capping resting upon the red syenites. The effusive rocks are found in the northeastern part of Buffelspan [585], in the high ridge from Houwater [496] to Wijdhoek [701], and appearing again at the other side of the Rustenburg road, where the effusives of the ridge are in contact with lujauritic rocks and can be followed in a northwesterly direction. On Tusschenkomst [331] and Welgeval [749] they are separated from the lujaurite by a shallow valley at the contact. Still more to the north we find the effusive rocks on Schaapkraal [12] and on Driefontein [888], where they are exposed in the valley of a rivulet, which flows in the direction of Rooderand [399]. On the northern farms of the Pilandsberg the high ridges of effusive rocks bend around parallel to the circumference of the complex; on the western farms they have their greatest development and almost entirely hide the deep-seated rocks.

The rocks of the country around the Pilandsberg.—The rocks which surround the Pilandsberg complex are the norites and granites of the Bushveld igneous complex and the quartzites and shales of the Pretoria series.

Norites and Pyroxenites: These rocks form the characteristic small hills (Pyramids, Zwartkoppies) parallel to the Magaliesberg range. They bend to the northwest in the neighborhood of Rustenburg, but the characteristic hills disappear long before they reach the Pilandsberg; much more to the north, on the farm Modderkuil [565], we see them again just in the continuation of those to the south of the Pilandsberg. The bands of magnetite are found to the southeast of the Pilandsberg. They end against the red syenites near the boundary of the farms Rhenosterfontein [867] and Rhenosterspruit [906], but are found again to the north of the Pilandsberg. We see that the whole southern part of the Pilandsberg is immediately surrounded by the basic rocks; on the farms Ledig [744] and Koedoesfontein [818] they are in immediate contact with lujaurites and allied rocks. Near the boundary of Zandrivierspoort [747] and Mahobieskraal [562] the isolated hills of aegirine-amphibole foyaites and the ridges of Magaliesberg quartzite come close together. At a small distance farther to the northwest and to the west the basic margin of the Bushveld com-

plex is again largely developed. It covered the whole region, which is limited to the south by the Schurvebergen and Zeerust Hills, to the west by the Marico Hills, and to the north by the Dwarsbergen.[1]

In following the basic margin along the western boundary of the Pilandsberg, we find quartzites in the northern part of Vogelstruisnek [602] which are in immediate contact with red syenites. More to the north the latter rocks border again upon norites. Near, and west of, the native *stadt* on Ruigehoek [426] norites rich in feldspars are exposed in the valley of a rivulet; they are the same rocks as those which are found to the south of the Pilandsberg, but show a pronounced schistose structure and a dip to the northeast. To the west the rocks become more basic, and near the contact with the quartzites on Davidskuil [142] very basic rocks were collected in the valley of a rivulet which is crossed by the road from the native *stadt* on Mabieskraal [620] to Janskop on Bierkraal [545]. They, too, show a pronounced schistose structure. Here the strike is about N. 15 W., and the dip is to the east-northeast.

On Tusschenkomst [446], to the east of the quartzite hill Janskop on Bierkraal [545], a series of hills consisting of schistose basic rocks can be followed in a north-northwesterly direction. Humphrey[2] mentions a peculiar feature of the pyroxenites, particularly noticeable on the farms Ruigehoek [426] and Zandspruit [181], where narrow bands of chromite, dipping to the east, have formed a band of comparatively high ground and an apparent stratification.

From all that has been said above, it is evident that the basic margin of the plutonic complex *is cut off abruptly* by the intrusion of the Pilandsberg.

Granites: The red granites of the igneous complex of the Bushveld are found to the east of the norites. The boundary between the two rock types crosses the Elands River in the southeastern part of Rhenosterfontein [867] and ends against the alkali syenites. The red granites are found all along the eastern part of the Pilandsberg; on Saulspoort [269], west of the Rustenburg road, the

[1] F. H. Hatch, *Trans. Geol. Soc. South Africa*, VII (1904), p. 1.

[2] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 81.

boundary between the norites and granites begins against the effusive rocks of the Pilandsberg complex and runs from there in a northeasterly direction. The occurrence of brecciated rocks with granite boulders in the hill behind the Saulspoort Mission station, which was already mentioned in my previous paper, has been studied in detail by Humphrey,[1] who found various types of igneous rocks. The relationship between these is very complicated. Syenite is seen to be intrusive into the effusive rocks and fragments of granite are found within the syenites and effusive rocks. Farther up the hill there is an extensive outcrop of granite which extends for some 800 yards along the face of the hill. Above this granite is found a diorite, and the crest of the hill is formed by effusive rocks. Breccias, in which granite occurs as included boulders, and also repeated outcrops of granite were found on Doornpoort [251] and Zuiverfontein [718] in the eastern marginal part of the Pilandsberg. Large boulders of red granite embedded in coarse red syenite are to be seen in the bed of the Rhenosterspruit on the farm Rhenosterspruit [609].

Pretoria series: The Magaliesberg Range, which from Rustenburg strikes in a northeasterly direction, comes to an abrupt end on Mahobieskraal [567], to the southeast of the Pilandsberg complex. Then the Pretoria beds bend to the west; near Bechuanaland they have a short northerly direction, and then return again to the east, passing at a distance of about 8 miles to the north of the Pilandsberg complex and forming the northern boundary of the igneous complex of the Bushveld.

Isolated hills of quartzite are found at several places to the east of the Pilandsberg. On Vogelstruisnek [602] they are in immediate contact with the red syenites. Other hills of quartzite occur on Tweelaagte [180], Vlakfontein [902], behind the native *stadt* on Mabieskraal [620], on Davidskuil [142], and still more to the north on Bierkraal [545]. From Janskop on Bierkraal the quartzite hills extend still more to the east, where they approach the northern boundary of the igneous complex of the Bushveld.

Between the Pilandsberg and the Marico River, the Upper Magaliesberg beds are missing from the normal sequence of the Pretoria series. They are represented by the isolated hills of

[1] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 87.

quartzite, which are entirely surrounded by rocks belonging to the igneous complex of the Bushveld and most probably were broken up in connection with the intrusion of this complex.

Dike rocks.—The first nepheline syenite of the Transvaal was discovered by Elie Cohen[1] in 1872, near the Hex River, between Renseburg and Rustenburg. He states that this rock forms the lower parts of the Zwartkoppies, where these hills bend to the northwest. The rocks collected by Cohen were described by E. A. Wülfing[2] in 1886 as porphyritic foyaites in which the nepheline only occurs in the groundmass.

In 1904 G. A. F. Molengraaff[3] collected nepheline syenites on the farms Elandsheuvel [255] and Tweede Poort [189]; these rocks are porphyritic foyaites in which nepheline occurs as phenocrysts. These rocks are described in the petrographical part of my previous paper. Since that time the sheet Rustenburg (sheet No. 4) has been mapped by the Geological Survey of the Transvaal, and it is shown that several dikes of these porphyritic foyaites intersect the rocks of the Bushveld complex, running from the Pilandsberg in a southeasterly direction.

Some of them even cut through the Magaliesberg Range to the east of Rustenburg and can be followed still farther to the south.

A fine-grained red syenitic rock was found by me to the north of the red hill on Rooderand [399], cutting through the norites in a nearly northerly direction. At the boundary of Groenfontein [302] and Bierkraal [545] near the quartzites, a porphyritic syenite was found in the basic rocks. On Plate XIV in the annual report for 1911 of the Geological Survey of South Africa it is shown that several syenitic dike rocks can be followed from the Pilandsberg in a north-northwesterly and northwesterly direction.

All these dikes cut through the norites and granites of the Bushveld, *and they have been intruded after the consolidation of the rocks of the Bushveld igneous complex.*

[1] E. Cohen in *Berichte über die XVI. Versammlung des Oberrheinischen Geologischen Vereins*, am 29 März, 1883, Stuttgart.

[2] E. A. Wülfing, "Untersuchung eines Nephelinsyenits aus dem mittleren Transvaal," *Neues Jahrb. f. Min. Geol. u. Pal.*, 7 Mai, 1888, Bd. II, p. 16.

[3] G. A. F. Molengraaff, "Preliminary Note on the Geology of the Pilandsberg;" *Trans. Geol. Soc. South Africa*, VIII (1905), 208.

Inside the Pilandsberg several dikes occur. Some dike rocks with the macroscopic appearance of the tinguaites form a band of comparatively high ground, because of their resistance to denuding agencies. On Boekenhoutfontein [889] near the boundary with Kafferskraal [890] a dike of this kind strikes N. 50 W.; it measures about 10 meters across and cuts through the foyaites with biotite; the contact with the foyaites is formed by a bent line, as well as the contact of a dike in the southeastern part of Koedoesfontein [649].

Near the boundary of Driefontein [889] and Nooitgedacht [148] I found a tinguaitic dike, 2 meters in diameter, with a sharp contact and a northeasterly strike, cutting through medium-grained nepheline syenites in the valley of a rivulet. Near the contact the rock has a glassy appearance; in the central part the structure is porphyritic. This dike dips steeply to the northeast. At the boundary of Olivenfontein [145] and Rooderand [398], in the valley to the south of the red syenites, a similar dike, which measures 5 meters across, is exposed.

The direction of these dikes agrees nearly with that of the dikes outside the Pilandsberg. In the western rivulet to the north of the houses on Driefontein [888], a tinguaitic dike or segregation, averaging 40 centimeters in width, has a blended contact with the surrounding lujaurites. It is rich in bronze-brown flakes of mica. Near the lujaurites the rock is very rich in aegirine; this mineral is often developed in spherulites which are up to 1 centimeter in diameter.

According to Humphrey,[1] dikes of foyaite, red syenite, nepheline syenite, and diorite occur in all parts of the Pilandsberg, and, in addition to these, there are many basaltic and tinguaitic varieties occurring in various parts. In the spruit on Saulspoort [269] a dike of red syenite cuts through the effusive rocks. A series of red "felsitic" dikes and blue-black glassy dikes, which were difficult of determination, and dikes of nepheline syenite traverse the red syenites. The dikes of nepheline syenite, which have their greatest development outside the Pilandsberg, seem to disappear into the

[1] "The Geology of the Pilandsberg," *Annual Report of the Geol. Survey of South Africa*, 1911, p. 85.

nepheline syenites in the central part of the complex. Dikes of foyaite were found traversing the red syenites of the central part.

From all that has been said above, it is evident that *the foyaites are the youngest rocks* of the Pilandsberg complex, while there is good evidence to show that the red syenite is older than some of the effusive rocks.

Pegmatites.—Dikes of pegmatite, which in many other nepheline syenite regions contain numerous rare minerals, were not met with during my visit. Coarse-grained pegmatitic segregations in the normal-grained rocks are of frequent occurrence, but the rare minerals were not found in much larger crystals than in the normal-grained varieties.

Pegmatites rich in eucolite are well exposed in lujauritic rocks from the hills to the north of the houses on Driefontein [888]. They consist principally of large crystals of feldspar, green nepheline, long crystals of aegirine, and carmine-red eucolite which is partly altered to catapleiite; they also contain some astrophyllite. The prisms of aegirine are up to 10 centimeters in length, and sometimes show a graphic intergrowth with feldspar. Near, and to the west of, the main road to Saulspoort [269] where it crosses the Rhenosterspruit in the northeastern part of Buffelspan [585], we found pegmatites in the aegirine-amphibole foyaites. Feldspars up to 10 centimeters in length, green nepheline, prisms of amphibole, and prisms or spherulites of aegirine are the main constituents; they also contain some fluorine. Amphiboles with a very small angle of optic axes *in which the plane of the optic axes is normal to the plane of symmetry*[1] occur in these rocks. In the southern part of Wijdhoek [701], near, and to the west of, the main road and to the south of the ridge of effusive rocks, we found pegmatites, which are very rich in astrophyllite and spherulites of aegirine, measuring up to several centimeters in diameter. They are found still farther to the southwest on Koedoesfontein [746] in a rivulet which joins the Wolvespruit, where numerous blocks of pegmatites and lujaurites could be collected; some of them are very rich in eucolite.

[1] H. A. Brouwer, "On Zonal Amphiboles in Which the Plane of Optic Axes of the Margin Is Normal to That of the Central Part," *Proceed. Kon. Akad. Amsterdam*, XVI (1913), 275.

The aegirine-biotite foyaites in the northwestern part of Boekenhoutfontein [889] contain pegmatitic segregations and small dikes in which feldspars, feldspathoids, and eucolite mineral and small pale-yellow needles occur. Often they are very rich in aegirine; this agrees with its tardy crystallization in most of the rocks of the region.

Finally, we found segregations in the lujaurites to the west of the common boundary post of Tusschenkomst [331], Leeuwfontein [429], and Wijdhoek [701]; they consist almost entirely of aegirine spherulites which are up to some centimeters in diameter.

Segregations rich in fluorine occur in the microfoyaites of Olivenfontein [745], and segregations rich in large aegirine spherulites occur in mesocratic foyaites of the valley, running in a north-south direction in the northeastern part of Buffelspan [585].

Humphrey mentions the occurrence of very coarse-grained pegmatites with much fluorspar on Doornhoek [134] and beautiful pegmatites, about half a mile from the homestead on Driefontein [888] on the main road to Buffelskloof (219).

Mechanism of intrusion of the Pilandsberg complex.—Since the rocks of the Pilandsberg complex are younger than the red granites and norites of the Bushveld igneous complex, and since the Pilandsberg is surrounded on three sides by norites and on one side by red granites, it seems to be beyond doubt that the space which is occupied by the Pilandsberg intrusive rocks was occupied, prior to the intrusion, by the norites and red granites of the Bushveld.

That the removal of the original rocks was not the result of folding is proved by the occurrence of a great number of vertical dikes of vast extension, which are genetically connected with the intrusion.

The hypothesis that the subsidence of crust blocks elsewhere was the cause of the intrusion of the magma and the hypothesis of laccolithic intrusion seem not to be applicable in the present case.

As has been stated by Humphrey, there can be no doubt that the Pilandsberg represents the remnant of what was once an important focus of eruption, and the hypothesis that the intrusive magma has filled up the cavities which were formed by volcanic outbursts of an explosive character seems to be applicable.

Tuffs and volcanic breccias are found all over the areas where the effusive rocks are developed. The main rock types of the Pilandsberg are disposed in concentric circles, of which the outermost consists of syenites and nepheline syenites and is followed toward the center by a ring of effusive rocks. The latter dip, with a few local exceptions, from the center outward, and the highest hills formed by intrusive rocks in the central area of the complex still carry a capping of volcanic rocks which have resisted denudation.

If the Pilandsberg is considered as the remnant of what was once a volcano and its subsidiary peripheral vents, this must have been of stupendous dimensions, since the intrusive rocks cover a surface whose diameter varies from 15 to 18 miles, the lavas having extended far beyond the periphery of the intrusives.

It is peculiar that in the territory of the Pilandsberg effusive rocks are found in large quantity between the granular rocks, whereas they do not occur in the surrounding granites and norites. The lavas, which must have extended far beyond its periphery, have entirely disappeared and do not even cap the hills of Magaliesberg quartzite, though at some places the quartzite is found in the immediate neighborhood of the Pilandsberg. It is very likely that in connection with the intrusion of the alkali rocks the roof has locally sunk down, and, while it has disappeared everywhere else in the neighborhood by erosion, we see the remains preserved just on those spots where the roof has given way.

Subsidences in ancient volcanic regions are by no means rare. Judd,[1] for instance, mentions the comparatively perfect state of preservation exhibited by the great volcano of Mull, if compared with that of the other great Tertiary volcanoes in the Hebrides. It can be shown that this difference is due to a central subsidence which took place in the Mull volcano. From the sections along the shores of the deep fiords it is evident that the basaltic lava sheets dip toward the central mass of eruptive rocks, the inclination increasing as we approach the volcano. Further, there is clear

[1] J. W. Judd, "On the Ancient Volcanoes of the Highlands and the Relations of Their Products to the Mesozoic Strata," *Quart. Journal of the Geol. Soc.*, XXX (1874), 256.

evidence of the existence of faults, the downthrow of which is in all cases toward the great central mass. A similar subsidence took place after the period of the eruption of acid lavas and before that of the basaltic lavas.

The state of preservation of the Pilandsberg complex and surrounding area is not very favorable to a study of the amount of subsidence in the sunken area. The lavas, which must have extended far beyond the mountain proper, have entirely disappeared; the junction of the intrusive rocks of the Pilandsberg with those of the Bushveld is not well exposed; and the amount of denudation in the area surrounding the complex cannot be estimated. This probable subsidence and the large dimensions of the plutonic body lead us to mention another hypothesis to explain the mechanism of intrusion of many batholites, which has been set forth by Daly.[1] He termed this process "overhead stoping"; it consists of a continued breaking free of roof blocks and a sinking down of the detached blocks into the magma, which consequently rises and occupies the place of the sunken fragments.

The cover of the intrusive rocks of the Pilandsberg entirely consists of lavas, the effusive equivalents of the intrusive rocks, and this is very common in batholitic intrusions from other parts of the world. How these facts are explained by overhead stoping has been elaborately discussed by Ussing[2] in a recent treatise on the geology of the country around Julianehaab. If a batholitic magma on one or more occasions during its intrusion has penetrated its cover, this will presumably lead to a volcanic outburst of catastrophic character, accompanied by the outpouring of lava flows and followed by a period of quiescence. After a time, when hot magma from below is brought into contact with the newly formed roof, the stoping process will continue, interrupted by few volcanic outbursts until the magma has cooled to its point of solidification.

In several batholites with a permanent cover of sedimentary rocks the stoping process came to an end and the magma was

[1] R. A. Daly, "Geology of the Ascutney Mountain," *Un. St. Geol. Surv. Bull. No. 209* (1903), p. 93; "The Mechanics of Igneous Intrusion," *Amer. Jour. of Science*, 4th series, XV (1903), and XXVI (1908).

[2] N. V. Ussing, "Geology of the Country around Julianehaab, Greenland," *Medd. om Grönland*, XXXVIII (1911), p. 302.

solidified before the earth's surface was reached, but the Pilandsberg alkali magma must have been very rich in mineralizing agents, which reduced its viscosity, and in such magmas the stoping process may go on when they near the earth surface and until the cover is penetrated. Volcanic outbursts cause an escape of the volatile substances, and the magma becomes more and more viscous, until a new supply of heat and mineralizers from below sets up stoping again. In fact, several rare minerals with a highly complex constitution, which are not stable at high magmatic temperatures, occur within the Pilandsberg rocks. Fluorine is a very common constituent, and, as their very name imports, fluorides must have reduced the viscosity considerably. Moreover, fluorine and other minerals in which we find direct evidence of the co-operation of mineralizers are regularly distributed in several rocks of this region, where they crystallized in the last cavities, thus proving that the mineralizing agents in part were regularly distributed until the final consolidation.

Of course, direct support would be given to the co-operation of overhead stoping if fragments which could only be derived from an original cover of the crystalline rocks were found among the rocks of the Pilandsberg complex, but Humphrey[1] mentions that all the close-grained rocks, which in the hand specimens very much resemble shales, proved themselves under the microscope to be devitrified lavas.[2] Particularly at those places in the northeastern part of the area where the granites are found to within a few hundred yards of the Pilandsberg complex it is of great interest to know whether these granites occur in their original position.[3]

Age of the Pilandsberg.—In the neighborhood of the Pilandsberg the rocks which formed the covering of the igneous complex of the Bushveld at the time of its intrusion most probably belonged to the

[1] "The Volcanic Rocks of the Pilandsberg, etc.," *Trans. Geol. Soc. South Africa*, 1912, p. 102.

[2] In my previous paper (*Oosprong en samenstelling der Transvaalsche Nephelien-syenieten*), p. 17, I mentioned having found shales in the valley to the north of the homestead on Houwater [496], but the rocks were not studied under the microscope.

[3] Cf. also H. A. Brouwer, "On the Formation of Primary Parallel Structure in Lujaurites," *Proc. Kon. Akad. Amsterdam*, 1912, p. 734.

Waterberg system; they have here been entirely removed by denudation. Humphrey mentions that there are no signs of the presence of Waterberg rocks among the stratified lavas, nor were any fragments of those rocks found among the volcanic breccias, while many examples of included granite boulders within the Pilandsberg rocks were found.

He concludes that the volcanic outbursts and the outpouring of lava postdated the removal of all of the sedimentaries of the Waterberg system in this neighborhood. No evidence is available about the age of the Pilandsberg rocks with regard to the Karroo system.

Of course, if the possibility of overhead stoping is admitted, the problem of the age of the Pilandsberg rocks is more complicated, but the question of the mechanism of intrusion is still too vague for further discussion.

OTHER OCCURRENCES OF NFPHELINE SYENITES AND ALLIED ROCKS

The occurrence of nepheline syenites on Leeuwfontein [320] and Zeekoegat [287] was discovered by Molengraaff in 1898.[1] The numerous variations of the Leeuwfontein foyaites in chemical and mineralogical composition and also the leucocratic and melanocratic dike rocks, bostonites, monchiquites, tinguaites, etc., were described. Liebenerite porphyries, like those which occur at Predazzo in the Tyrol and at Alnö (Sweden), are also associated with the nepheline syenites of this region.

D. Draper discovered nepheline syenites on Walmansdal [116] to the northwest of Zeekoegat [287]. The rocks to which J. A. L. Henderson[2] gave the name hatherlite were also collected on Leeuwfontein [320]. As was stated by Molengraaff,[3] the name hatherlite is not applicable because the old powder factory "Eerste fabrieken" or "Hatherley factory" is situated to the south of the Magaliesberg Range and has nothing to do with the factory on Leeuwfontein [320].

[1] G. A. F. Molengraaff, "Note on Our Present Knowledge of the Occurrence of Nepheline Syenite in the Transvaal," *Trans. Geol. Soc. South Africa*, VI (1903), p. 89.

[2] J. A. L. Henderson, *On Certain Transvaal Norites, Gabbros, and Pyroxenites and Other South-African Rocks*, London, 1898.

[3] G. A. F. Molengraaff, *Geology of the Transvaal* (Johannesburg, 1904), p. 46.

In the *Annual Report of the Geological Survey of the Transvaal* for 1903, A. L. Hall[1] gives an account of the rocks from Leeuwfontein [320] and Zeekoegat [287] which is followed by a petrographical description of these rocks and those on Walmansdal [116] and the newly discovered occurrence on Franspoort [426].

On Leeuwkrall [396], about 5 km. to the northwest of Hamanskraal station, H. Kynaston[2] discovered two occurrences of syenitic rocks, the southern one locally graduating into nepheline syenite. It is a porphyritic foyaite similar to some of the dike rocks which occur to the southeast of the Pilandsberg. On Rietfontein [451] and Spitskop [463] an interesting occurrence of nepheline syenites within the red granites was discovered by Hall[3] in 1910; and Wagner[4] mentions the occurrence of a dike of basic camptonite cutting through the Waterberg sandstones on Buffelspruit [1920], which means probably that nepheline syenites occur at a deeper level.

The intrusion on Leeuwfontein [320].—To the east of Pretoria, near Franspoort [426], the ridges of quartzite belonging to the Pretoria series bend to the southeast; the Magaliesberg quartzites have been extended in length, while the Daspoort and Timeball quartzites were strongly pressed in a direction slightly oblique to the strike of the strata.

In describing the dislocations connected with the intrusion of the igneous complex of the Bushveld, Molengraaff[5] supposed that at those places where the circumference of the complex shows a convex curve interesting phenomena may be expected. We saw that the Pilandsberg intrusion is located where the Pretoria series,

[1] A. L. Hall, "On the Area to the North of the Magaliesberg Range and to the East of the Pietersburg Railway Line," *Annual Report of the Geol. Survey of the Transvaal*, 1903, p. 38.

[2] H. Kynaston, "On the Area Lying North-West of Pretoria, between the Magaliesberg Range and the Salt Pan," *Annual Report of the Geol. Survey of the Transvaal*, 1905, p. 29.

[3] *Annual Report of the Geol. Survey of the Transvaal*, 1910.

[4] P. A. Wagner, "Note on an Interesting Dyke Intrusion in the Upper Waterberg System," *Trans. Geol. Soc. South Africa*, 1912.

[5] G. A. F. Molengraaff, *Proc. Geol. Soc. of South Africa*, 1905; "Criticism on Messrs. A. L. Hall and F. A. Steart: On Folding and Faulting in the Pretoria Series," *Trans. Geol. Soc. South Africa*, VIII (1905), 7–15.

which from Rustenburg strike in a northeasterly direction, bend again to the west, and the nepheline syenite intrusions to the northeast of Pretoria are found where the ridges of quartzite bend to the southeast. The foyaite intrusion on Franspoort [426] is entirely surrounded by Magaliesberg quartzite and is clearly intrusive in them. Near the intrusion on Leeuwfontein [320], which borders "felsites" only on the north, the Magaliesberg quartzites cover a large surface in consequence of numerous faults. Following the valley of the Pienaars River to the north, we see a succession of red "felsites" with an approximate east-west strike and a varying dip to the north, alternating with eruptive breccias, conglomerates, and basic effusive and dike rocks. More to the north, on Roodeplaat [314], they are covered by shales and syenitic rocks of doubtful age, and on Paarderfontein [338], at a great distance from the foyaite, dikes of tinguaitic and andesitic character, which in part are connected with the intrusion on Leeuwfontein [329], cut through the sandstones and conglomerates of the Waterberg system. The chemical composition of a tinguaite of Paardenfontein [338] closely agrees with that of the normal foyaites on Leeuwfontein [320]. The small differences are similar to those which characterize the nepheline syenites and accompanying tinguaite dikes from other regions.

An interesting dike of basic camptonite has recently been described by Wagner.[1] It occurs on Buffelspruit [1920] in the Waterberg district and cuts through Waterberg sandstone. This proves again that the intrusion of nepheline syenite with which the dike most probably is connected is younger than the Waterberg sandstones.

The "felsites" are the effusive equivalents of the intrusive rocks on Leeuwfontein [320]. The liebenerite porphyries, which in the southern part of Roodeplaat are exposed over a long distance in the valley of the Pienaars River, show the same characteristics as the liebenerite porphyries of Alnö and the Tyrol. But also the dense weathered rocks of which the mineralogical composition could not be recognized under the microscope belong to the alkali

[1] P. A. Wagner, "Note on an Interesting Dyke Intrusion in the Upper Waterberg System," *Trans. Geol. Soc. South Africa*, 1912.

rocks, as was proved by chemical tests. After treating the powder with hydrofluoric acid, only 0.4 of its weight was evaporated, and a simple calculation makes evident that the Al partly occurs in feldspars, partly in feldspathoids. Microchemically the residue gave a strong soda reaction and a very feeble potash reaction. From this it is evident that "felsites" which are the effusive equivalents of the intrusive rocks are genetically connected with the alkali rocks of the intrusion on Leeuwfontein [320].

An exact petrographical examination will greatly assist in the determination of the stratigraphical place of the different "felsites." Identity in age for the felsophyres of the Waterberg district and of the phonolites of Leeuwfontein [320] would seem to be in the highest degree improbable.

From a petrographical point of view there is much resemblance between the rocks of Leeuwfontein [320] and those of the Pilandsberg; the association of foyaites of varying composition with red syenites and effusive rocks is a common characteristic. The rocks on Leeuwfontein [320] near the old dynamite factory are principally red syenites and red hololeucocratic feldspar rocks; in the southern part the *leeuwfonteinites* with accompanying porphyritic equivalents occur. The porphyritic rocks sometimes form well-defined dikes.[1] Leeuwfonteinite porphyry and monzonite porphyries are found between Leeuwfontein [320] and Franspoort [426] and along the path to Derde Poort [469]. The numerous varieties of foyaite occur near the boundary of the farms Leeuwfontein [320] and Zeekoegat [287]; they will be described in detail in a forthcoming petrographical paper. The normal foyaite of this region is a coarse-grained, leucocratic, aegirine-amphibole foyaite. In varieties rich in feldspathoids (particularly sodalite) aegirine is the only dark constituent; they pass into rocks which are nearly free from feldspar (*tawites*). Rocks very rich in titanite (*pienaarites*) occur at several places. The rocks on Leeuwfontein [320] differ from those of the Pilandsberg by the absence of rare minerals in the latter rocks. In other nepheline-syenite regions the rare minerals are

[1] The leeuwfonteinites are the same rocks as Henderson's hatherlites (anorthoclase syenites), cf. Henderson, *On Certain Transvaal Norites, Gabbros, and Pyroxenites and Other South-African Rocks*. They contain much plagioclase and their composition varies between that of the alkali monzonites and that of the alkali syenites.

also often limited to the aegirine foyaites and the arfvedsonite foyaites and are wanting in the foyaites with barkevikitic amphibole. The rare minerals and a not very small quantity of lime in the magma seem to exclude one another (compare the analysis of the normal foyaite of Leeuwfontein, which has been given in my previous paper). The association of foyaites with leeuwfonteinites which besides barkevikite also contain plagioclase makes it probable that the CaO content of the common mother-magma was rather considerable.

The rocks of the neighborhood of Leeuwfontein [320], which hitherto have been studied under the microscope, belong to the following groups:

1. Aegirine foyaites
   Leucocratic rocks
   Pienaarites (melanocratic rocks rich in titanite)
2. Aegirine-amphibole foyaites
3. Tawites
4. Feldspar rocks
5. Aegirine-foyaite porphyries
6. Aegirine-amphibole foyaite porphyries
7. Leeuwfonteinites
8. Leeuwfonteinite porphyry and monzonite porphyry
9. Tinguaite porphyries
10. Monchiquites
11. Augitites
12. Andesitic camptonites
13. Doleritic nepheline basalts
14. Diabases
15. Liebenerite porphyries
16. Bostonites
17. Phonolites

H. Kynaston[1] mentions that *the foyaite of Walmansdal* [116] is clearly intrusive in the "felsites."

Nepheline syenite region to the west of Lydenburg.[2]—This region covers a surface which has about the same extension as that on Leeuwfontein [320]. It is surrounded by red granites and occurs

[1] H. Kynaston, "The Geology of the Country Surrounding Pretoria," Explanation Sheet I, *Geol. Surv. of the Transvaal*, 1907, p. 28.

[2] A. L. Hall, in *Annual Report Geol. Surv. of the Transvaal*, 1910.

close behind the zone of ultra-acid rocks which Hall discovered at the boundary between the granites and the basic margin of the igneous complex of the Bushveld. The specimens which Mr. Hall kindly put at my disposal during my stay in the Transvaal are melanocratic lujaurites and lujaurite porphyries, which sometimes show a schistose structure. The colorless minerals are sometimes very subordinate and microscopically the rocks seem to consist almost wholly of fine needle-shaped crystals of aegirine. These very melanocratic lujaurites were rare in the Pilandsberg complex, but seem to cover the greater part of this newly discovered occurrence.

Foyaites also occur, and it is interesting to find the association of lujaurites with leucocratic feldspathoid rocks (*urtites*), which consist chiefly of nepheline. The association of lujaurites and urtites in the peninsula of Kola (they received their names from the same place—Lujavr Urt) is also a characteristic of this district.

An isolated mass of strongly metamorphic limestone is inclosed within the alkali rocks.

ORIGIN AND AGE OF THE NEPHELINE SYENITES AND ALLIED ROCKS

It does not seem improbable that the nepheline syenites have originated from the same sources as the granites and norites of the Bushveld. The formation of the basic margin in the main intrusion of the Bushveld proves that magmatic differentiation took place on a very large scale. Toward the periphery the rocks become more and more basic, while granites occupy the central portion. When tested in detail, the view of general increase of basicity from the center toward the periphery requires modification. Hall[1] has described a zone of ultra-acid rocks with 97 per cent SiO_2 in the red granites close to the boundary with the norites to the west of Lydenburg. He considers these rocks as a product of extreme differentiation, which could take place near the basic margin, when the viscosity of the granitic magma was already strongly increased. That sometimes the acid and basic rocks pass gradually into one another possibly depends on the depth to which the complex has been exposed by erosion.

[1] A. L. Hall, "Note on Certain Widespread Ultra-Acid Rocks Occurring along the Margin of the Bushveld Granite, etc.," *Trans. Geol. Soc. South Africa*, XIII (1910), p. 10.

If ultra-acid rocks have differentiated from the granitic magma, the residual magma will be enriched in Al_2O_3, and alkalies with regard to SiO_2 and its composition will more or less agree with that of the nepheline syenites. This kind of differentiation may have taken place on a much larger scale at a greater depth, which has not been exposed by denudation. It is interesting to find an occurrence of nepheline syenites on Rietfontein [451] and Spitskop [463], close behind the zone of ultra-acid rocks.

The coarse textures, the rather indefinite order of crystallization, the numerous poikilitic structures,[1] the abundance of fluorine and rare minerals with a highly complex constitution, which are characteristic for many of the nepheline syenites in the Transvaal, make it probable that these rocks crystallized from a residual magma in which the volatile constituents were concentrated and which may have crystallized at rather low temperatures. Some of the nepheline syenites are certainly younger and may be considerably younger than the sandstones and conglomerates of the Waterberg system; the time at which the different intrusions have risen to the present level and the time at which they have consolidated may have varied between wide limits.

The age of an intrusive rock is determined by the time of its consolidation, and it is very probable that the alkali magmas remained fluid during a very long period of igneous activity. When these magmas which are rich in volatile substances shall crystallize will greatly depend upon the eventual loss of these substances, which may have been the immediate cause of crystallization quite as much as of any actual cooling.[2]

Only some characteristic features of the various igneous rocks have been dealt with; as has been stated above, it does not seem improbable that the nepheline syenites and allied rocks have originated from the same sources as the granites and the norites of the Bushveld. To the petrologist there are many very interesting problems with regard to the origin and age of the different rock types which would repay further research.

[1] H. A. Brouwer, "On Peculiar Sieve Structures in Igneous Rocks Rich in Alkalies," *Proc. Kon. Akad. Amsterdam*, November, 1911.

[2] A. Harker, *The Natural History of Igneous Rocks*, 1909, p. 186.